

# HST/COS Spectroscopy of H1504+65

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**Abstract.** We present new ultraviolet spectra of the peculiar white dwarf (WD) H1504+65, obtained with *COS* on *HST*. H1504+65 is the hottest known WD ( $T_{\text{eff}} = 200\,000\text{ K}$ ) and has an atmosphere mainly composed of C and O, augmented with high amounts of Ne and Mg. This object is unique and the origin of its surface chemistry is completely unclear. We probably see the naked core of either a C–O WD or even a O–Ne–Mg WD. In the latter case, this would be the first direct proof that such WDs can be the outcome of single-star evolution. The new observations were performed to shed light on the origin of this mysterious object.

**Keywords:** White dwarfs, atmospheres, abundances

**PACS:** 97.20.Rp, 97.10.Ex, 97.10.Tk

## INTRODUCTION

H1504+65 is a faint blue star that was identified as the counterpart of a bright soft X-ray source [6]. Spectroscopically, it is a member of the PG 1159 class but, within this class H1504+65 is an extraordinary object. It was shown that it is not only hydrogen-deficient but also helium-deficient. From optical spectra it was concluded that the atmosphere is primarily composed of carbon and oxygen, by equal amounts [10]. Strong neon lines were detected in soft X-ray spectra taken with the *EUVE* satellite and in a Keck spectrum, and a high abundance of neon was derived [12]. The origin of this exotic surface chemistry (C = 49%, O = 49%, Ne = 2%, mass fractions) is completely unclear. We have speculated that H1504+65 represents the naked C–O core of a white dwarf. Another, even more exciting possibility is that we see the eroded C–O envelope of a O–Ne–Mg white dwarf. This is corroborated by our analysis of a *Chandra* soft X-ray spectrum [14], which allowed the detection of magnesium.

H1504+65 turns out to be the hottest single WD ever analyzed with model atmospheres ( $T_{\text{eff}} = 200\,000\text{ K} \pm 20\,000\text{ K}$ ,  $\log g = 8.0 \pm 0.5$ ), only rivaled by the hot DO KPD 0005+5106 (see Wassermann et al. in these proceedings, and [8]). Because of this extremely high temperature, a unique photospheric absorption-line spectrum can be observed with *Chandra-LETG*. It shows a wealth of lines from highly ionized species (O VI, Ne VI – Ne VIII, Mg V – Mg VIII). But the spectral analysis of the X-ray data is seriously hampered by heavy line blanketing of iron-group elements. In principle, we can account for this in our synthetic spectra, but two problems prevent a detailed quantitative analysis of relatively weak absorption lines from light metals within the Fe-group forest. First, accurate line positions are unknown for the majority of the Fe-group lines. Second, the bulk of the Fe-group lines from very high ionization stages (a single Fe X UV line was recently discovered in a *FUSE* spectrum, see Werner, Rauch, & Kruk, these proceedings; and [15]) are completely unknown. Consequently, effects of Fe-group line

blending on other weak metal lines cannot be calculated with sufficient precision. Nevertheless, we have roughly estimated the Mg abundance to about 1%, an amount similar to the Ne abundance. If this strong overabundance (20 times solar) can be confirmed, then that would strongly support the idea that H1504+65 is a O–Ne–Mg WD.

This means that H1504+65 might have been one of the “heavy-weight” intermediate-mass stars ( $8 M_{\odot} \lesssim M \lesssim 10 M_{\odot}$ ) that form white dwarfs with electron-degenerate O–Ne–Mg cores. Evolutionary models [3] predict strong Ne and Mg overabundances in the C/O envelope. Another strong argument in favor of this idea would be the detection of sodium, which would be direct evidence for C-burning. The models predict that the  $^{23}\text{Na}$  abundance at the bottom of the C/O envelope is comparable to that of neon (main isotope  $^{20}\text{Ne}$ ) and magnesium ( $^{24,25,26}\text{Mg}$ , see Fig. 34 in [3]). Unfortunately, we were not able to detect Na lines in the *Chandra* spectrum beyond doubt because of, again, heavy metal-line blanketing.

## RELEVANCE OF H1504+65

At present it is uncertain under which circumstances super-AGB stars (i.e. the massive counterparts of AGB stars that ignite carbon but do not proceed to further stages of nuclear burning) produce O–Ne–Mg WDs or explode as electron-capture SNe producing NSs (e.g. [7]). This uncertainty mainly arises from modeling uncertainties in mass-loss and mixing processes. The possibility that H1504+65 is a O–Ne–Mg WD is remarkable, because evidence for the existence of such objects is rather scarce [9]. Evidence from single massive WDs is weak, and the most convincing cases are WDs in binary systems. Strong Ne overabundances are found in novae [5] or in eroded WD cores in LMXBs [4]. If we can prove high Mg and Na abundances in H1504+65, then this would be the most compelling case for the existence of a single O–Ne–Mg WD, i.e. a post super-AGB star.

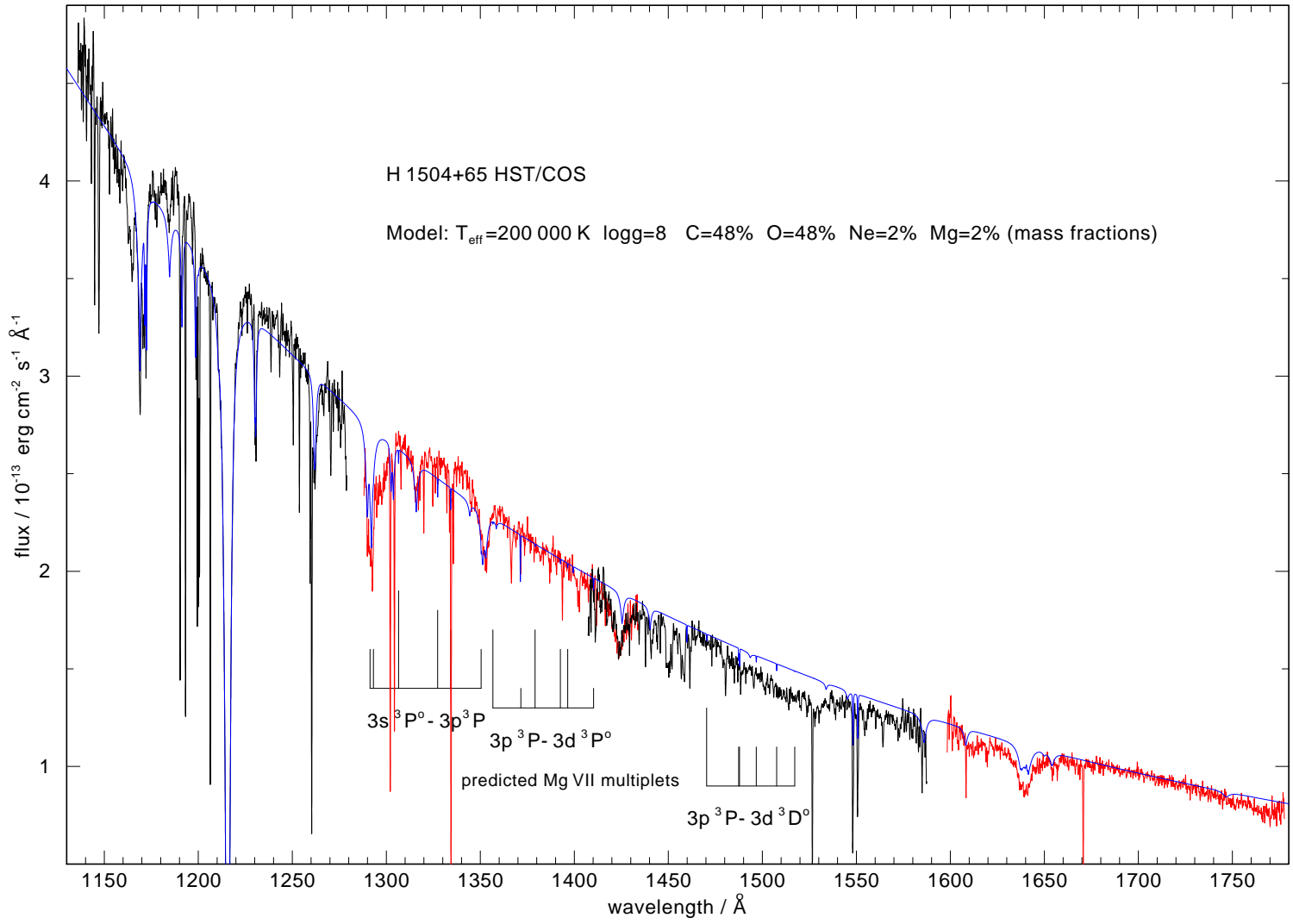
It is interesting to note that the recently discovered relatively cool white dwarfs ( $T_{\text{eff}} \approx 20\,000\text{ K}$ , see Dufour et al., these proceedings, and [1]) with almost pure carbon atmospheres (so-called hot DQs), as well as the O-rich white dwarfs (He-dominated atmospheres with  $\text{O}/\text{He} \approx 0.01$  and  $\text{O} > \text{C}$ , by number, and  $T_{\text{eff}}$  around  $10\,000\text{ K}$ ) reported by Gänsicke et al. (these proceedings, and [2]), could be evolutionary linked to H1504+65. The latter, in particular, could well be O–Ne–Mg white dwarfs.

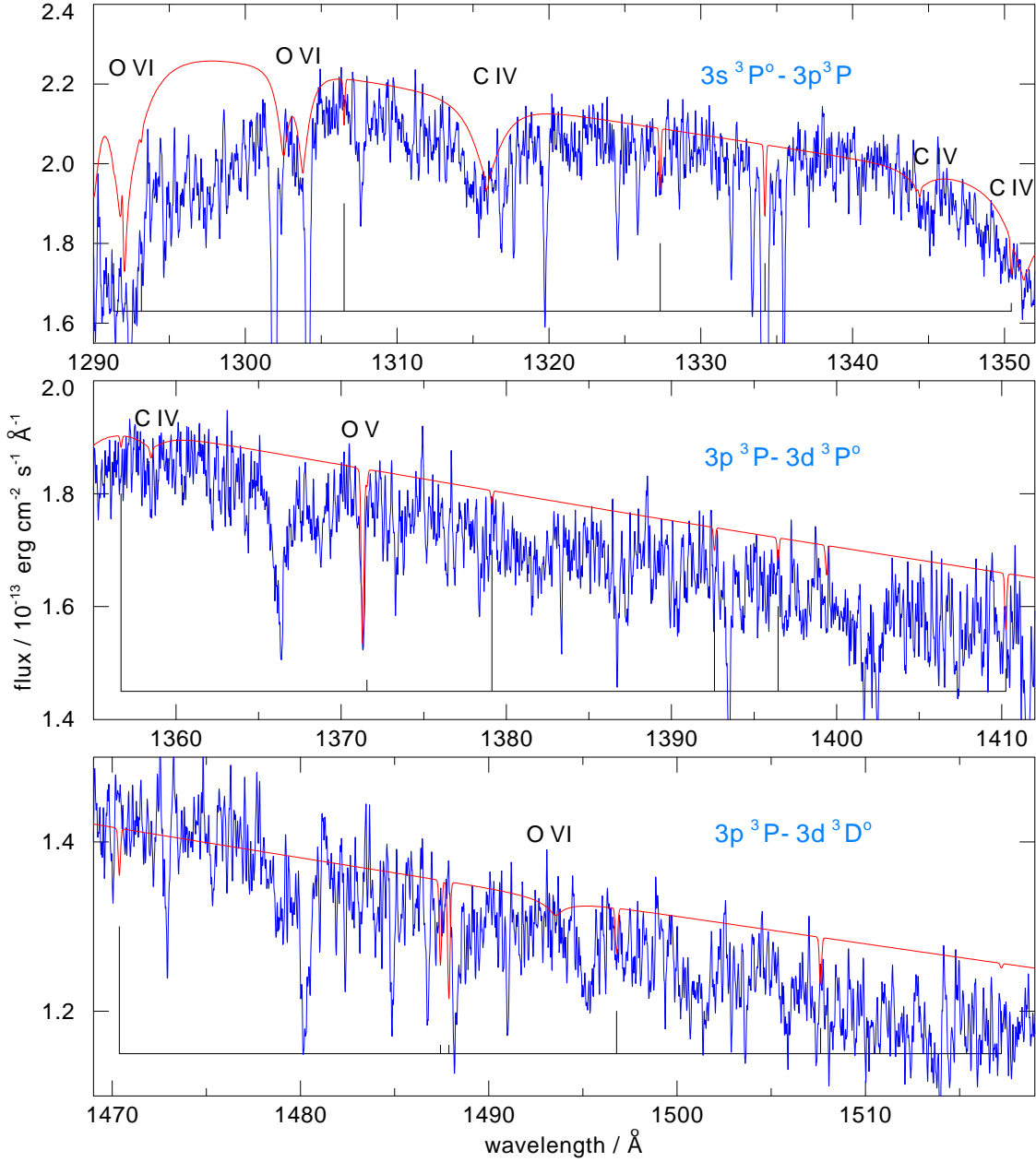
H1504+65 also challenges stellar evolution theory relevant for super-AGB stars, because it cannot explain how H1504+65 has lost its H-rich and He-rich envelopes and why it exposes its metal-rich core. Our detailed abundance determination of the H-deficient PG 1159 stars has shown that the efficiency of convective overshoot during He-shell flashes is stronger than hitherto assumed in evolutionary calculations. In analogy, the determination of the strange surface chemistry of H1504+65 challenges super-AGB evolutionary models, which are unable to explain the observed helium-deficiency.

## HST/COS UV SPECTROSCOPY

Our immediate motivation to perform new observations is the search for Mg and Na lines in the UV spectrum of H1504+65 and to determine the respective abundances. The UV

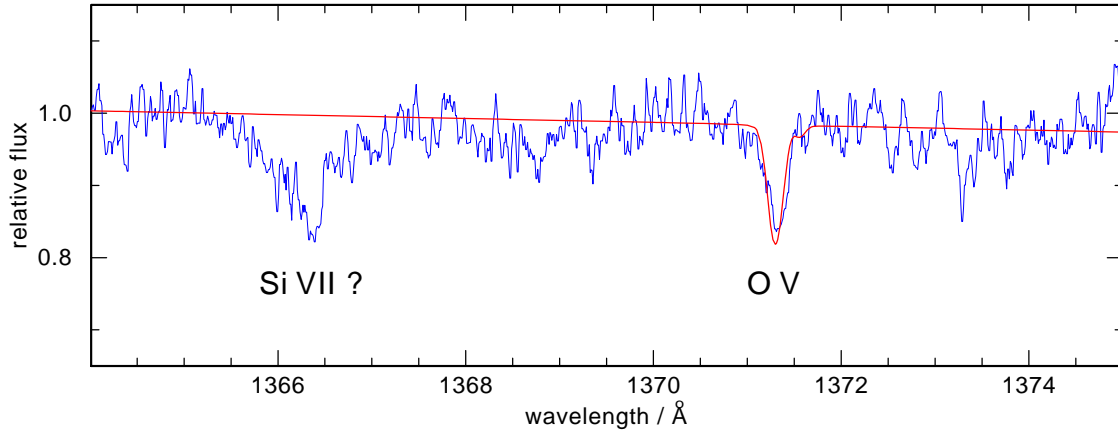
**FIGURE 1.** *HST/COS* observation of H1504+65 compared to a model. Three Mg VII multiplets, predicted by the model, are marked.





**FIGURE 2.** Details of the spectra in the vicinity of the three Mg VII multiplets marked in Figure 1.

range is certainly free of iron-group lines. Hot central stars of planetary nebulae ( $T_{\text{eff}} \approx 100\text{ kK}$ ) show iron lines of Fe V – Fe VII in the UV. But H1504+65 is so hot that the dominant ionization stages of the Fe-group elements are IX and X. Almost all respective lines are located in the EUV and soft-X-ray regions. Hence, we should be able to detect and analyze even very weak lines of light metals in the UV. We expect to see Mg and Na lines if these elements are abundant on the 1% level. There are three multiplets of Mg VII and two multiplets of Na VI located in the 1150–1700  $\text{\AA}$  region.

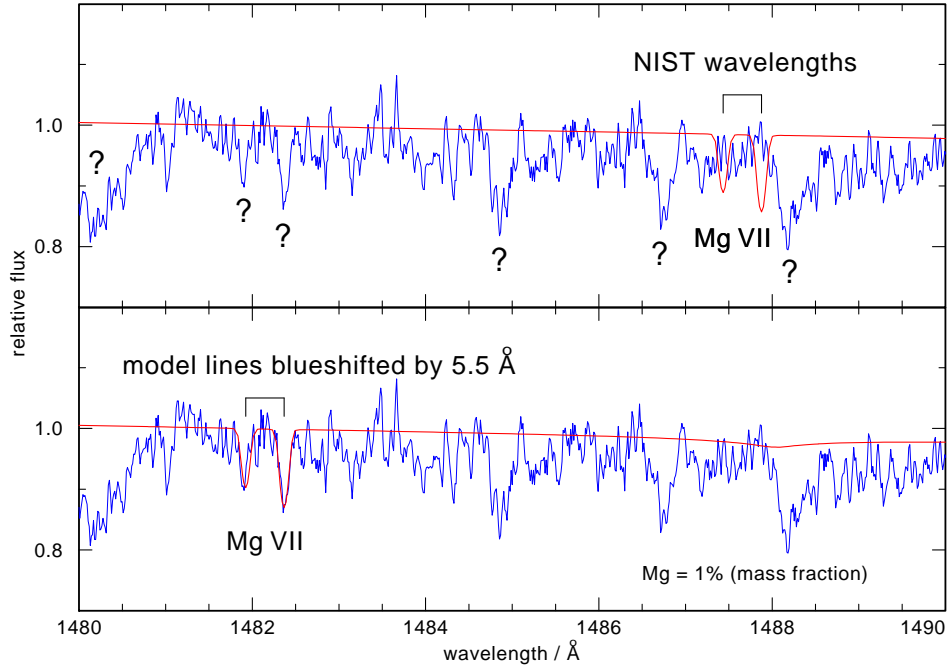


**FIGURE 3.** Detail of the *COS* and model spectra in the vicinity of the O v 1371 Å.

The *Cosmic Origins Spectrograph* (*COS*) was installed at *HST* in May 2009. On Oct. 24, 2009, *HST* recovered from a shutdown of its science data formatting (SIC&DH) onboard computer, an event that spoiled our observations because they were performed shortly afterwards, on the same day. *COS* spectroscopy of H1504+65 was performed with gratings G130M and G160M during one orbit each. The wavelength range 1150–1760 Å was covered with about 0.1 Å resolution. Data inspection revealed problems with the flux calibration, related to the recovery of SIC&DH. It turned out that the *COS* detectors worked outside of their normal temperature range. As a consequence, image distortions were large enough to place stim pulses – required for the distortion correction – off the detector. Our request for repetition of the observations was accepted. This repetition was performed on May 25, 2010.

Figure 1 displays the four *COS* spectral segments compared to a spectrum computed from a model with parameters found from our earlier multi-spectral analyses mentioned above. Almost all prominent line features are from C IV, O VI, and Ne VIII, hence, elements (and ions) that were already identified in *FUSE* spectra [14]. New identifications are lines from O V, Si VII, and Ne VII. It is remarkable that, without fine-tuning, our model fits the O v 1371 Å line very well (Figs. 2, 3), indicating that, in conjunction with the fit to O VI lines,  $T_{\text{eff}}$  is now known to an accuracy of about 3% [11].

A close inspection of the data reveals about 70 unidentified photospheric lines. Many of them are probably Ne VII multiplets, but the problem is that their positions are rather uncertain (within several Å). This seriously hampers the identification of other species. In particular, the identification of Mg VII will be very difficult. Figure 2 shows the regions around the three Mg VII multiplets in more detail. It is not obvious that the predicted lines have counterparts in the observation. The two strongest predicted lines are shown in even more detail in Fig. 4 (top panel). No lines are visible at the NIST wavelength positions. Like for Ne VII, the Mg VII line positions are uncertain. It could well be, that some of the unidentified features in Fig. 4 are Mg VII lines. For example, shifting the computed Mg VII lines by 5.5 Å (lower panel) puts them in place of two observed lines. A systematic analysis of Mg VII and Ne VII level energies will be necessary in order to obtain reliable results.



**FIGURE 4.** Top: Detail of the *COS* spectrum in the vicinity of two Mg VII lines marked in the bottom panel of Figure 2. The predicted Mg VII lines are not present in the observation. A number of unidentified photospheric lines are visible (question marks). Bottom: Computed spectrum shifted by 5.5 Å.

A number of other line features are from the following potential candidates (but often we face again problems with line position accuracy): Na VII, Mg VIII, Si VIII, Ar VIII, Ca X, and Fe VIII. The reality of many features is confirmed by the presence of similar features in a high-resolution, high-S/N *HST/STIS* E140H archival spectrum of the PG1159-type central star of NGC 246 ( $T_{\text{eff}} = 150\,000$  K,  $\log g = 5.7$  [13]).

**Acknowledgements** TR is supported by German Aerospace Center (05 OR 0806).

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